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**Air/Ground Wind Shear Information Integration - Flight Test Results**  
**David Hinton, NASA Langley Research Center**



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# **Air/Ground Wind Shear Information Integration - Flight Test Results**

**David A. Hinton**

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# Air/Ground Wind Shear Information Integration Flight Test Results

David A. Hinton

## ABSTRACT

An element of the NASA/FAA wind shear program is the integration of ground-based microburst information on the flight deck, to support airborne wind shear alerting and microburst avoidance. NASA conducted a wind shear flight test program in the summer of 1991 during which airborne processing of Terminal Doppler Weather Radar (TDWR) data was used to derive microburst alerts. High level microburst products were extracted from TDWR, transmitted to a NASA Boeing 737 in flight via data link, and processed to estimate the wind shear hazard level (F-factor) that would be experienced by the aircraft in the core of each microburst. The microburst location and F-factor were used to derive a situation display and alerts. The situation display was successfully used to maneuver the aircraft for microburst penetrations, during which in situ "truth" measurements were made. A total of 19 penetrations were made of TDWR-reported microburst locations, resulting in 18 airborne microburst alerts from the TDWR data and two microburst alerts from the airborne in situ measurements. The primary factors affecting alerting performance were spatial offset of the flight path from the region of strongest shear, differences in TDWR measurement altitude and airplane penetration altitude, and variations in microburst outflow profiles. Predicted and measured F-factors agreed well in penetrations near microburst cores. Although improvements in airborne and ground processing of the TDWR measurements would be required to support an airborne executive-level alerting protocol, the feasibility of airborne utilization of TDWR data link data has been demonstrated.

# **OUTLINE**

- **Introduction and System Concept**
- **Flight Test Procedure**
- **Results**
  - **F-factor Algorithm Performance**
  - **System Alerting Performance**
- **1992 Enhancements**
- **Summary**

## Research Goal

Under the terms of the Integrated Wind Shear Program, NASA, the FAA and industry have jointly developed solutions to the wind shear hazard to commercial transports. The NASA efforts are concentrated in airborne aspects such as hazard characterization, aircraft performance impact, advanced in situ and forward-look sensor technology, and flight deck integration. The FAA efforts have been concentrated in ground side aspects such as crew training (ref. 1) and ground-based detection systems such as low-level wind shear alerting systems and Terminal Doppler Weather Radar (TDWR). The TDWR system has proven its capability to detect the microburst phenomenology in tests and operational demonstrations, but experiences suggest (ref. 2) that the information is not reaching flight crews in a timely matter or in a form that is compatible with existing and planned onboard wind shear detection systems.

In 1990 a Memorandum of Agreement between NASA and the FAA was implemented with a major program element to "Demonstrate the practicality and utility of real-time assimilation and synthesis of ground-derived wind shear data to support executive level cockpit warning and crew-centered information display." The goal can be divided into subgoals of identifying ground-based information products required on the flight deck to derive a crew-centered hazard index and rapidly transmitting this data to the flight deck.

# **Research Goal**

**Reduce wind shear risk through integration of TDWR and airborne system capabilities.**

## **Approach:**

- Identify TDWR information products required for airborne processing of wind shear hazard index and executive-level crew alerting.**
- Demonstrate feasibility of data link and airborne utilization of TDWR information in an operational environment.**

## Ground Rules

Ground rules were established for the conduct of this program. The key ground rule was that neither the existing TDWR system nor the current division of responsibilities and roles between air traffic control and pilots would be altered. The TDWR system was to remain unchanged because years of testing have demonstrated its microburst detection capability, the system design was essentially frozen for production, and even minor changes would be prohibitively expensive. Rather than change the system, those high level products produced by TDWR that are required for airborne processing were to be identified and provided to an aircraft via data link. The emphasis was to provide an executive level warning (requiring immediate corrective or compensatory action by the crew). Such a warning requires a very low nuisance alarm rate, on the order of 1 nuisance per 250 hours of system operation. A nuisance is defined as an alert received when system alert threshold conditions exist but do not produce a hazard to the aircraft.

The air/ground roles of the proposed system are tailored to reflect current ATC/pilot roles. The TDWR is to classify events as a microburst and provide location and microburst parameters to the airborne system. The airborne component will quantify the threat, compare to a threshold, and annunciate. The concept is analogous to other ground systems providing meteorological data such as runway visual range, wind, and ceiling. The decision to continue is made on the aircraft based on required minima and operating procedures.



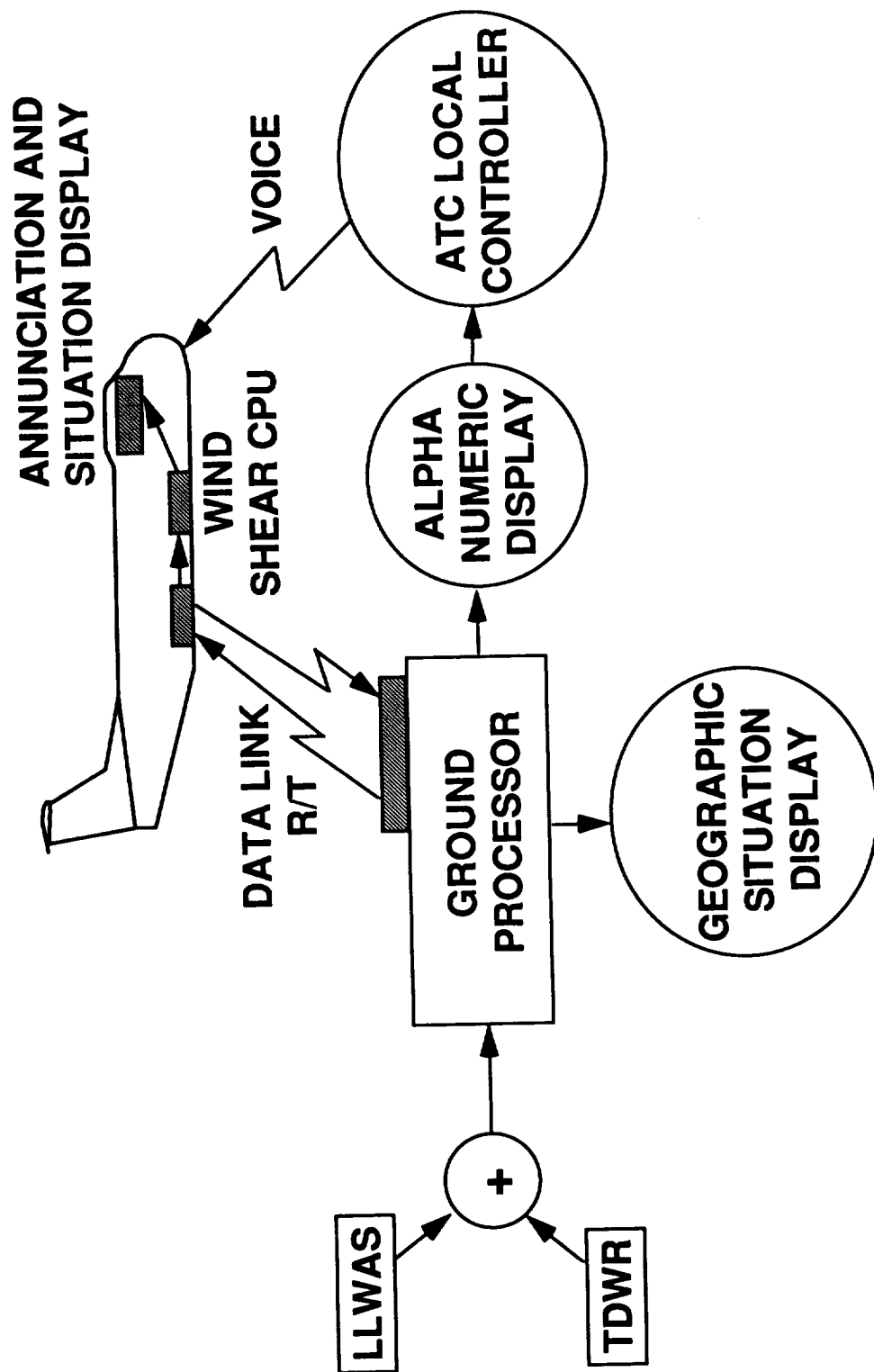
# **Ground Rules**

- Do not change the ground systems or current ATC/pilot roles.
- Identify ground products needed for uplink to support time critical information processing and display.
- Task tailored air/ground roles for TDWR integration:
  - Ground: Classify and locate
  - Airborne: Quantify and annunciate
  - Downlink status of airborne warning to ATC.
- Focus research on technology integration/evaluation.

## System Architecture

The baseline TDWR system consists of a radar, a ground processor to identify regions of divergence and classify them as microbursts, a geographic situation display to depict microburst locations relative to runways and approach paths to the ATC tower supervisor, and an alphanumeric ribbon display for presenting wind shear and microburst information to the local controller for voice transmission to pilots. A typical message from the local controller is "Microburst alert, threshold wind 140 at 5, expect a 50 knot loss two mile final." The additions to the TDWR system required to support the NASA alerting concept are a cockpit server software package to extract the necessary TDWR data for transmission over a data link, the data link receiver/transmitter, airborne algorithms to compute the wind shear hazard from TDWR supplied data, and annunciation and display. Only air to ground data link is required to provide airborne alerting. The intent of the down link is to provide the ATC system with information that a wind shear alert has been generated by the airborne system. No changes to the existing TDWR system are required to support this concept.

# System Architecture



## Operational Concept

The current TDWR operational concept is to detect microbursts by examining radar-observed wind velocity information for regions of divergence. When the radar detects a divergence of greater than 15 meters per second over a distance of at least 1 kilometer, a shape algorithm draws a microburst icon around the divergence region. "Wind shear" icons are drawn around divergence regions of at least 7.5 meters per second. The microburst is then quantified for ATC and pilots by the divergence value. The actual hazard to the aircraft depends heavily, though, on the scale length of the divergence, i.e., the change of wind per unit distance, or shear (ref. 3). Existing airborne wind shear systems as well as those under development derive an F-factor hazard index (ref. 3) that is based on wind change per unit distance and down draft. To provide airborne executive level alerting from TDWR information, an estimate must be made of the wind shear in the microburst and the down draft component. The information required for this estimate are readily available from the TDWR system. Since (at a readily available level) the TDWR produces a single velocity and distance number for each microburst, insufficient data are available to estimate the shear along arbitrary paths through the event. The airborne F-factor estimate tested in this study describes the threat only in the core of the event. The core F-factor estimate is then combined on the aircraft with microburst location information to determine if an alert should be given.

# Operational Concept

- Using available high-level TDWR products, estimate shear and F-factor in 1 kilometer region about core of microburst outflow.
- Combine F-factor and microburst location with respect to aircraft, to derive executive-level warning and situation display.
- System does not predict F-factor along arbitrary flight path, only predicts hazard in core of outflow.

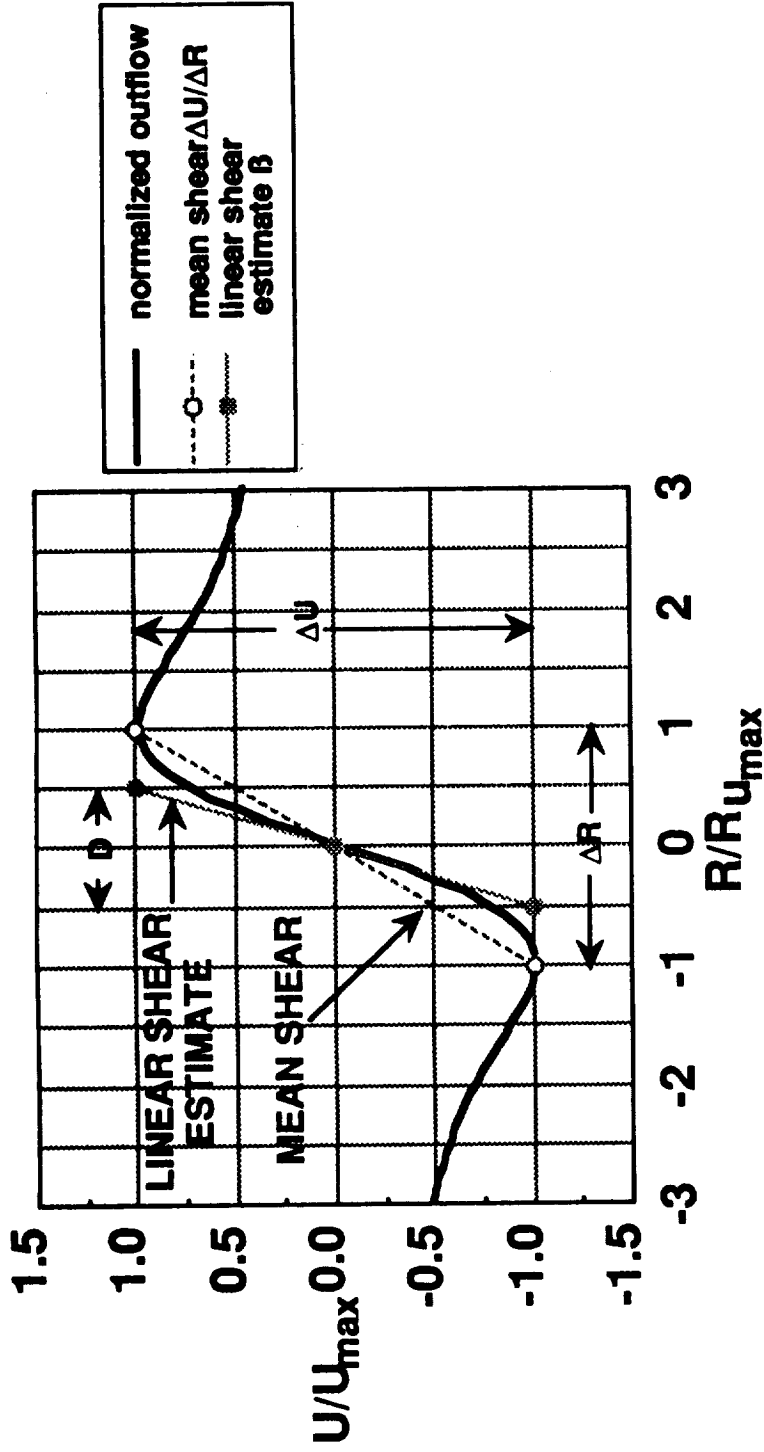
### Least-Square Estimate of Linear Shear

The wind shear within a microburst can be estimated from the wind change and scale length information provided by the TDWR and an assumed wind profile. The TDWR information describes the endpoints of the peak-to-peak winds and the assumed wind profile is used to derive information about the wind field between the peaks. The horizontal wind profile of the analytical Oseguera/Bowles microburst model described in reference 4 was used to estimate the least-squares shear value over a distance  $D$  about the core of the microburst. Since aircraft performance degradation from wind shear requires shear lengths on the order of 1 kilometer, or greater, a value of 1 kilometer for  $D$  was used in the experiment.

The microburst F-factor can be estimated from the shear value just determined and an estimate of the down draft in the event. Mass continuity considerations are used to estimate down draft over the same interval as the shear. The resulting equations, as originally derived by Bowles (ref. 3) are shown on the adjacent figure. The information required from the TDWR to estimate F-factor is the wind change ( $\Delta U$ ), the scale length of the wind change ( $\Delta R$ ) and the altitude of the radar beam in the microburst core.

Each microburst icon is composed of numerous divergence segments, each one degree apart in radar azimuth. Each divergence segment has its own wind change and length. In this experiment the  $\Delta U$  and  $\Delta R$  sent to the aircraft was determined as follows. If 5 or fewer segments define an icon then send the maximum  $\Delta U$  value. If this test fails then if 20 or fewer segments define an icon send the second largest  $\Delta U$  value. If more than 20 segments define an icon then send the 90th percentile segment  $\Delta U$  value. In practice, nearly all icons consisted of less than 20 segments and either the largest or next largest divergence value was normally sent. The  $\Delta R$  value was determined by examining the shear value of each segment in the icon and choosing the 85th percentile shear value. A  $\Delta R$  value was then determined that would produce this 85th percentile shear when divided into the transmitted  $\Delta U$  value. As an example, one icon penetrated in the 1991 flight tests (event 143) was defined by 4 segments having  $\Delta U$  values of 17.1, 18.9, 22.6, and 20.2 meters/second and  $\Delta R$  values of 3140, 3460, 4500, and 4210 meters, respectively. The corresponding shear values were 5.45, 5.46, 5.02, and 4.80 meters/second/kilometer. Since four segments defined the icon the largest  $\Delta U$  value (22.6) was transmitted. The 85th percentile shear value was the second largest (5.45) which produced a transmitted  $\Delta R$  value of 4150 meters (rounded to the nearest 10 meters).

# LEAST SQUARE ESTIMATE OF LINEAR SHEAR



$$\beta = 4.1925 \frac{\Delta U}{\Delta R} \left[ \left( \frac{\Delta R}{D} \right)^2 - \left( \frac{\Delta R}{D} \right)^3 \frac{\sqrt{\pi}}{2.2424} \operatorname{erf} \left( 1.1212 \frac{D}{\Delta R} \right) \right]$$

$$F = \beta \left[ \frac{V_g}{g} + \frac{2h}{V} \right]$$

## Alert Criteria

The TDWR data link provided the required data to estimate the microburst core F-factor and to depict the TDWR-derived microburst icons on a cockpit moving map display. In order to issue an executive-level alert, a microburst icon must exist on the projected instantaneous trajectory of the aircraft (defined by the centerline of the track-up moving map display), the range to the icon must be less than 1.5 nautical miles, and the core F-factor estimate must be at least 0.105. Note that in a classical microburst wind field the strongest wind gradient and F-factor exists in the core of the event, where the winds are weakest, while very weak wind gradients and F-factors exist in the vicinity of peak wind outflow. Since the TDWR-produced microburst shapes tend to enclose the peak-to-peak wind field, it is logical to assume that the shapes will overestimate the region of strong shear. Since insufficient data was available to determine which region within the icon contained the strongest shear, an alert was generated when any part of an icon intersected the flight path. The alert threshold is consistent with thresholds specified in FAA TSO-C117 for the certification of reactive wind shear devices and the 1.5 mile range is consistent with proposed crew procedures and the supporting alerting strategies.



# **Alert Criteria**

**Executive level alert is given when:**

- 1. A TDWR microburst icon intersects extended flight path.**
- 2. The F-factor of that icon is at least 0.105.**
- 3. The range to the icon is less than 1.5 nautical mile.**

## Flight Test Procedure

The TDWR data link concept was tested during NASA combined sensor flight tests conducted at Orlando, Florida and Denver, Colorado in June and July of 1991. The tests provided the opportunity to measure microburst winds with an array of remote sensors (TDWR, airborne radar, and infrared) and correlate those remote measurements with aircraft in situ wind shear measurements taken during microburst penetration. In addition to the TDWR research aspect, the TDWR system was also used operationally to predict microbursts, maneuver the aircraft for penetrations, and monitor flight safety criteria such as storm reflectivity values. Both for flight safety and for later data correlation, microburst penetrations were conducted on a track either toward or away from the TDWR to minimize the effects of any microburst asymmetry.

The flight tests were conducted in cooperation with the MIT Lincoln Laboratory at Orlando and the National Center for Atmospheric Research (NCAR) at Denver. Both Lincoln Lab and NCAR developed cockpit server software to extract the required parameters from the TDWR and format the data for transmission to a NASA ground station via modem and dedicated phone lines. Only low cost hardware was required to complete the data link to the aircraft. The data was transmitted at 1200 baud over an MFJ Enterprises MFJ-1270B TNC packet radio system. The data transmitted over the data link consisted of the  $\Delta U$ ,  $\Delta R$ , radar beam altitude, and coordinates of each microburst icon, as well as overhead data such as the GMT time of the beginning of the TDWR radar scan, number of icons in the data link message, and checksum. Each data link message required 14 bytes for overhead data plus 25 bytes per microburst icon. This data was transmitted approximately once every 60 seconds and the elapsed time between the beginning of a TDWR radar antennae sweep and the receipt of that data onboard the aircraft was on the order of 30 seconds. Onboard the aircraft the icons were displayed on a moving map display and used to maneuver the aircraft for microburst penetrations.

## **Flight Test Procedure**

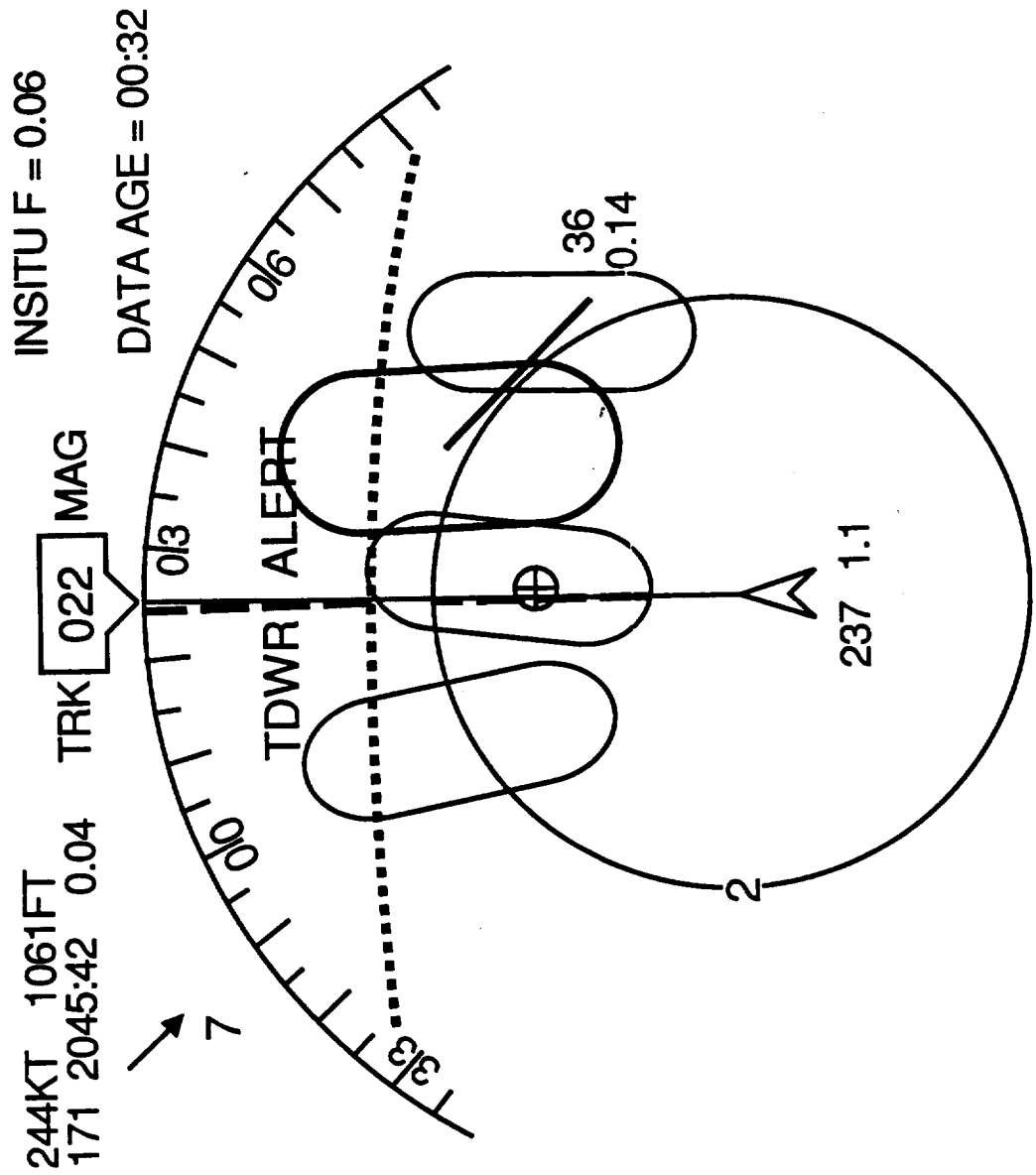
**TDWR information integration concept tested during combined sensor flight tests at Orlando and Denver onboard NASA Boeing 737, summer 1991.**

- Cockpit server TDWR software developed by MIT Lincoln Lab/NCAR.**
- Data provided via 1200 baud modem to VHF packet radio system. Required data = Delta V, diameter, radar beam altitude, and location and shape of each microburst icon.**
- TDWR data and alerts displayed on moving map display. Display used to maneuver aircraft for encounters.**

## Moving Map Display

The TDWR icon information was presented on a moving map display, along with supporting flight state parameters, and recorded on video tape for later analysis. The supporting data included the TDWR data age (elapsed time since last data link reception) and in situ F-factor in the upper right corner; true airspeed, time, radar altitude and inertial wind vector in the upper left corner; groundspeed and barometric altitude below the ownship symbol; and magnetic track angle above the track scale. Microburst alerts generated by the onboard computation and criteria were displayed by the message "TDWR ALERT" in red letters just below the track scale. The wind change and F-factor of each icon were shown numerically by labels that stepped from one icon to the next at the rate of about one icon per second (to reduce display clutter) and by color coding the icons. White was used to draw icons with F less than 0.105, amber for icons between 0.105 and 0.15 F, and red for icons with F-factors at or above 0.15. Also shown on the display were the limits of TDWR coverage and a waypoint which could be transmitted from the TDWR operator to accurately locate places of interest such as gust front boundaries, microburst cores, or predicted microburst locations. This display is not intended to represent a format that should be implemented for fleet operational use. The display was intended as an aid to data analysis as well as a tool for situational awareness during research flights.

The accompanying display sketch was drawn from a video tape of the approach to event 143 on June 20, 1991. Four microburst icons are ahead of the airplane and a waypoint transmitted by the TDWR operator is on the flight path at a range of about 1.5 miles. The aircraft has a groundspeed of 237 knots and the radar altimeter value is 1061 feet. A TDWR alert has been generated by onboard logic and is displayed. The dotted line just beyond the nearest icon represents a 30 kilometer range ring from the TDWR site, which is behind the aircraft.



## Results

The simple data link hardware proved very reliable at both deployment locations both while on the ground preparing for takeoff as well as while flying at low altitude 30 to 40 kilometers from the antennae site. The situation display combined with voice information from the TDWR proved invaluable for 15 to 30 minute projections of the weather situation, positioning the aircraft to intercept microbursts that were being predicted but not yet developed, maneuvering with respect to active microbursts, and subsequent data analysis. The situation display was used for maneuvering the airplane to penetrate active microbursts and for assessing the strength of those microbursts before penetration. The voice link was used for other operational data such as reflectivity at the surface and aloft, short term microburst predictions, and general weather trends.

During the two week deployment at Orlando the NASA aircraft penetrated 19 weather events that were generating TDWR icons at the time of penetration. Numerous other events were also encountered such as gust fronts, rain shafts, and divergent flows that had not yet strengthened to the point of generating an icon or decaying microbursts that were no longer producing icons. These other events are not included in this analysis. During a three week deployment at Denver the only observed microbursts were above flight safety reflectivity limits or could not be reached. Hence all data presented here is from the 19 icon penetrations in the Orlando area.

The data is analyzed from two perspectives. The first issue was the performance of the F-factor estimation algorithm. The second issue was the overall alerting performance of the TDWR system (TDWR, airborne processing, and alerting criteria) during the flight tests.

## **Results**

- TDWR data link proved reliable
- Situation display extremely useful for aircraft positioning as well as post-flight data analysis.
- 19 microburst icons penetrated at Orlando, none at Denver.
- Results analyzed for F-factor algorithm performance and for alerting performance.

## F-Factor Algorithm Performance

While the overall alerting performance analysis uses data from all 19 icon penetrations, evaluation of the F-factor estimation algorithm can be done only in those cases where the airplane passed through the region described by the estimator, which is in or very near the core of the microburst. Early in the flight tests it became apparent that the TDWR depicts microbursts with multiple icons, typically three or four, to locate areas of larger and smaller divergence ( $\Delta U$  magnitude). All icons associated with a microburst were treated equally by the airborne F-factor estimator although not all icons contained a center of divergence. Observation by TDWR operators, who could observe flight path as well as radar reflectivity and doppler velocity in real time, indicated that penetration of an icon could miss the divergence core by a kilometer or more. Later flights used the TDWR operator waypoint data link function to help locate the desired cores of the microbursts.

To evaluate the F-factor algorithm a selection criteria was established to determine which penetration data sets were applicable. The selection was based on TDWR radar velocity plots overlaid with aircraft trajectory. To include a penetration in the F-factor data set two criteria must be met; 1) that the TDWR velocity plot show a well-defined microburst outflow, and 2) that the flight path intersect the core of this outflow. Only five of the 19 events satisfied this criteria. Three of the five events were achieved during multiple penetrations of a single microburst on the final day of test flights, at growing, near peak, and decaying periods of the event. Event numbers were assigned to each data block of interest during the deployments. The five core penetrations are events 81, 134, 142, 143, and 144.

For comparisons between the F-factor estimator and in situ measurements, the TDWR radar scan taken closest to the time of airplane penetration was chosen. The average error between the TDWR F-factor estimator and in situ was only 0.02 F with the largest error being 0.04 F. The primary factors affecting the estimation, to be discussed in more detail, were differences between TDWR radar measurement altitude and airplane altitude in the microburst, and errors in estimating the one kilometer shear from TDWR peak-to-peak winds.

All TDWR radar reflectivity, velocity, and shear maps were provided to NASA by the MIT Lincoln Laboratory.



# **F-factor Algorithm Performance**

## **Event selection criteria:**

- Using TDWR velocity plots with aircraft trajectory overlay, determine that:

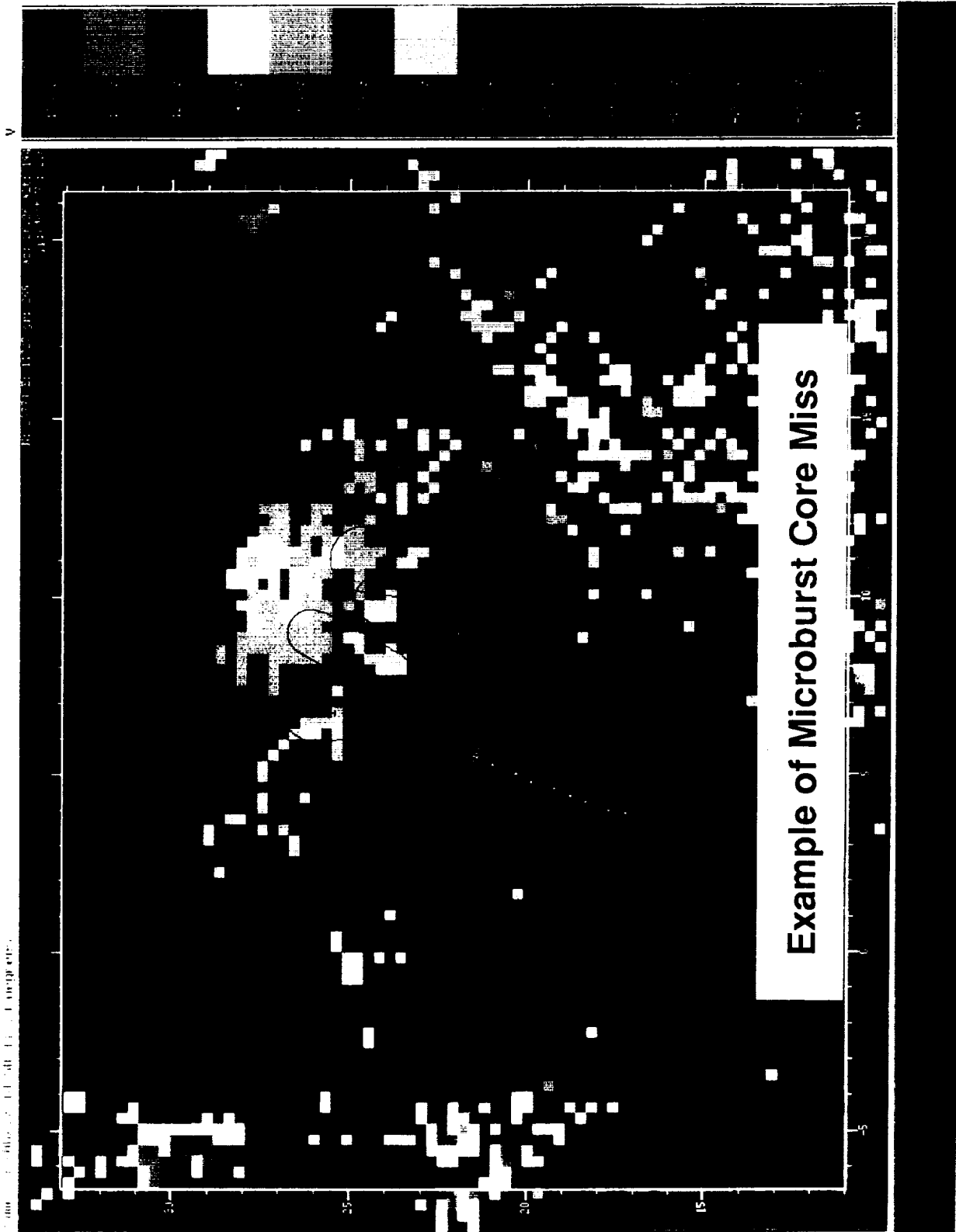
1. A well-defined outflow existed.
2. Aircraft path intersected core of outflow.

## **Criteria met by 5 of 19 microburst icon penetrations:**

- F-factor estimate from TDWR data agreed with in situ F-factor within 0.04, with average error of 0.02.
- Principle factors affecting hazard index estimate were measurement altitude and shear estimate from TDWR information.

# TDWR Plot of Missed Microburst Core and Microburst Core Penetration

These two plots show examples of a microburst icon penetration that did not encounter the core region described by the F-factor estimation algorithm and a penetration through a microburst core. The first event is not included in the set of five core penetrations. The second plot shows the airplane in the core of the penetration cataloged as event 142. Note in the second plot that the flight path passes through the doublet of highest doppler velocity return.



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## Speed and Altitude Effect on F-Factor

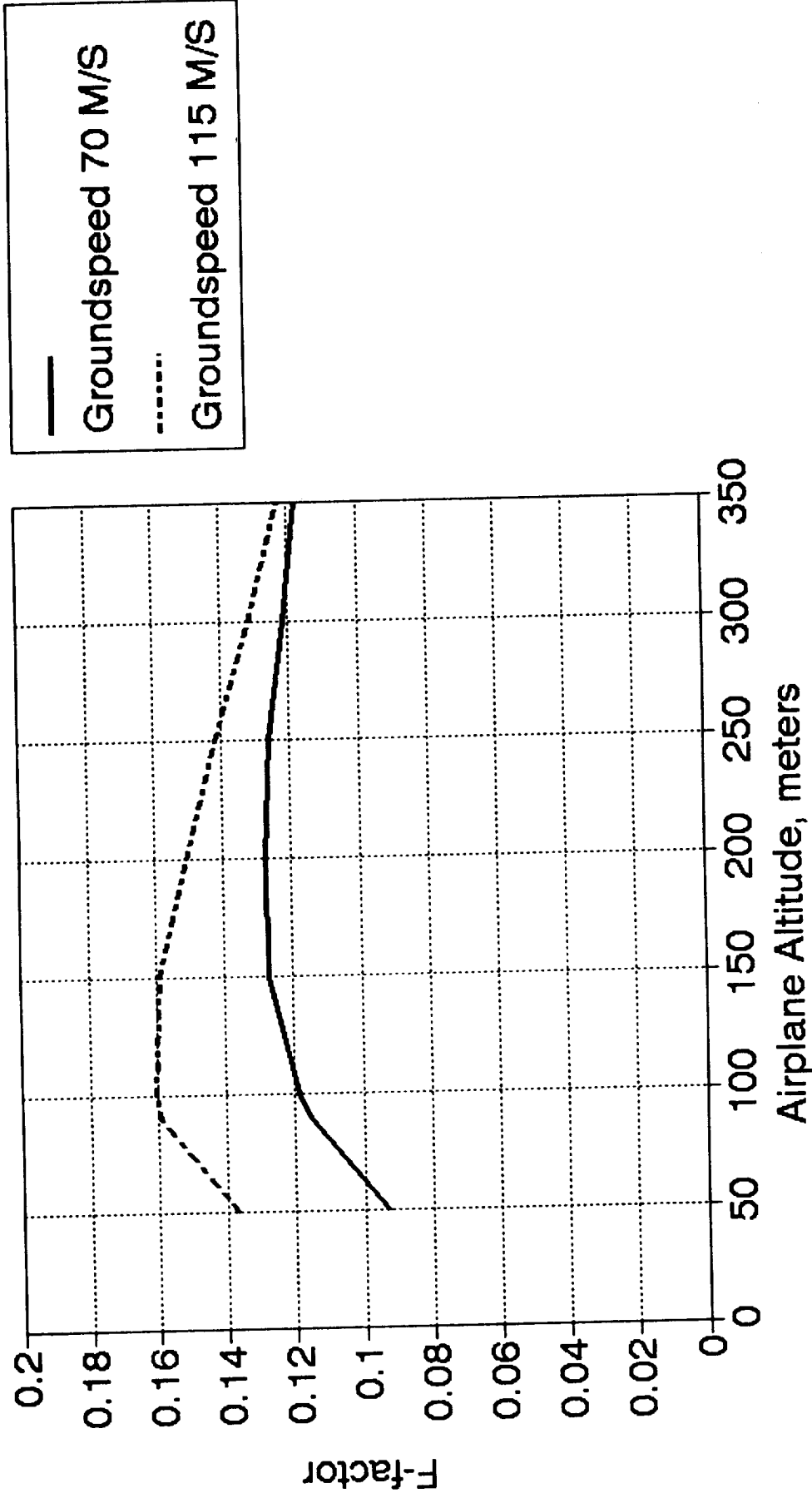
As the altitude of microburst penetration increases above the altitude of maximum outflow, the horizontal wind change decreases while the down draft increases. Since the F-factor experienced by the airplane is proportional to horizontal wind gradient multiplied by groundspeed and down draft divided by airspeed, the horizontal component of F-factor tends to decrease with increasing altitude while the vertical component tends to increase with altitude. At normal approach speeds the change in the two components tend to be of similar magnitude. The result is that the F-factor does not vary greatly with altitude above the altitude of maximum outflow up to altitudes where microbursts no longer pose a safety threat (about 1000 to 1500 feet). Below the altitude of maximum microburst outflow both horizontal winds and vertical winds decrease, leading to reduced F-factor. At the high speeds used in the microburst flights, however, the down draft contributes less to the total F-factor and the measured F-factor does tend to decrease with altitude. The plot shows variation in the altitude-corrected TDWR F-factor estimation with altitude at a groundspeed of 70 and 115 meters per second (136 knots and 223 knots) for a given microburst. The two speeds approximate normal approach speed and the NASA microburst penetration speed. The plot assumes that the altitude of maximum outflow is 90 meters and that the radar measurement is taken at that altitude. At 70 meters/second the change in F-factor from 90 meters to 350 meters is less than 0.01, while at 115 meters/second the change is nearly 0.04. The equation used to provide the TDWR altitude correction is presented next.





# Speed and Altitude Effect on F-Factor

Altitude-Corrected TDWR F-Factor



## F-Factor Altitude Effect

The trend of relatively constant F-factor with variations in altitude was used as an assumption in the TDWR F-factor estimation algorithm. Although aircraft speed was used in the F-factor algorithm, the altitude of the aircraft was not included in any way. The divergence measured by the radar was used directly and the altitude of the radar beam in the microburst was used in the estimation of the vertical wind. In effect, the F-factor estimate was assuming a penetration at the radar beam altitude. In the events penetrated the radar beam was typically at altitudes of 150 to 220 meters above ground, depending on range of the event from the radar, while the airplane typically flew through the event at 300 to 350 meters above ground. The analytical microburst models described in references 4 and 5 include a shaping function which describes the change in microburst outflow with altitude. These models base the shaping function on mass continuity, boundary layer friction, and vertical wind profiles produced by the Terminal Area Simulation System (TASS) numerical microburst model, which has been extensively validated against observed microburst data (references 6 and 7). The shaping function  $p(h)$  provides the ratio of outflow speed to maximum outflow speed at any arbitrary altitude. Given this shaping function, the shear estimate ( $\beta$ ) at any altitude can be expressed as the shear at the altitude of maximum outflow multiplied by  $p(h)$ .

$$\beta = \beta' p(h) \quad (1)$$

Where  $\beta'$  is the shear at the altitude of maximum outflow. We can express F at any altitude as:

$$F_1 = \beta' p(h_1) (V/g + 2h_1/V) \quad (2)$$

and

$$F_2 = \beta' p(h_2) (V/g + 2h_2/V) \quad (3)$$

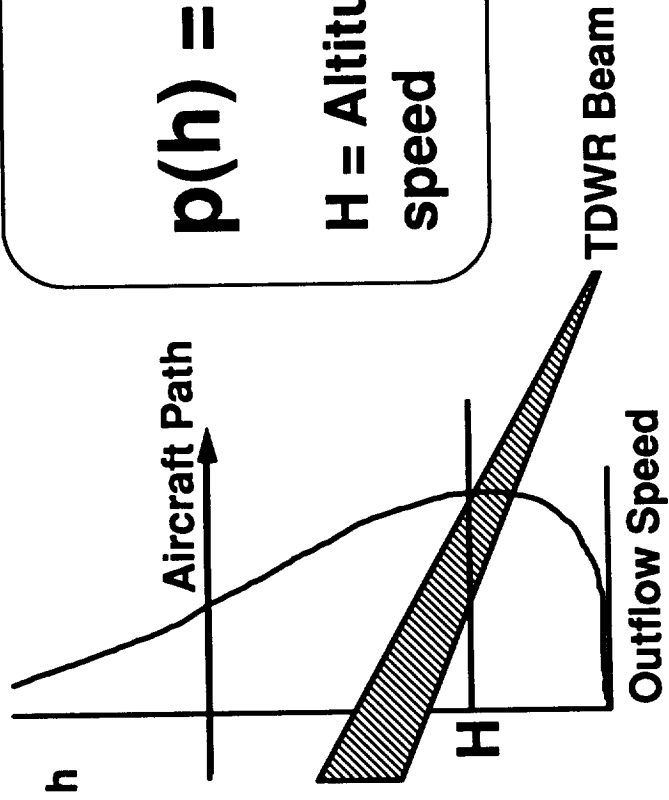
or by rearranging 2 and 3:

$$F_2 = F_1 \frac{p(h_2) (V/g + 2h_2/V)}{p(h_1) (V/g + 2h_1/V)} \quad (4)$$

Equation 4 was used as an altitude correction algorithm where  $F_1$  is the uncorrected TDWR F-factor estimation,  $h_1$  is the TDWR radar beam altitude, and  $h_2$  is the airplane altitude.  $F_2$  then becomes the F-factor estimate at the airplane altitude.

# F-factor Altitude Effect

TDWR measurement of wind divergence taken at different altitude than aircraft penetration. Altitude shaping function in NASA analytical wind shear model can provide correction.



$$p(h) = \frac{e^{-0.22h/H} - e^{-2.75h/H}}{0.7386}$$

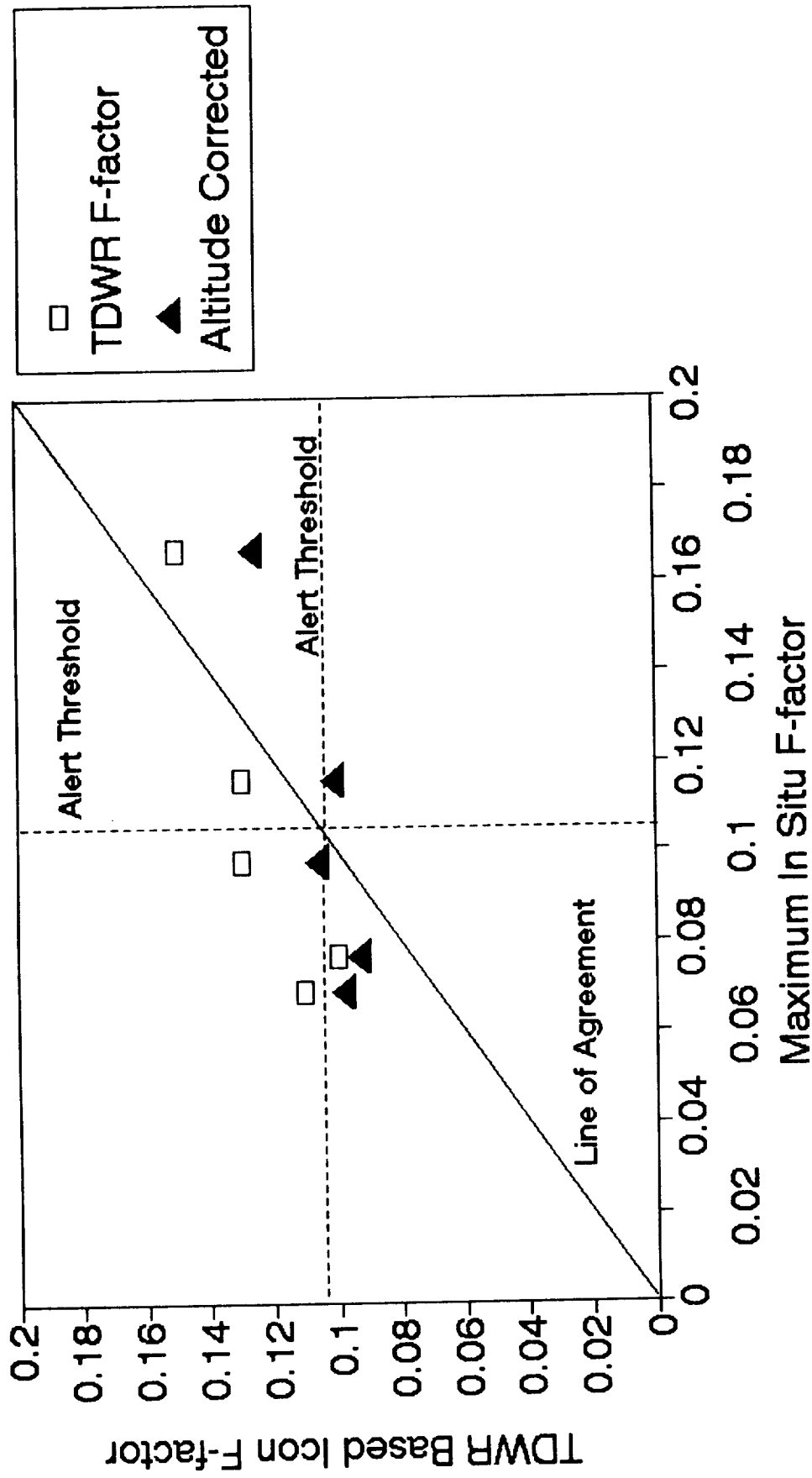
$H$  = Altitude of maximum outflow speed

## TDWR Based F-Factor and In Situ F-Factor

Shown in this plot is the F-factor estimated from TDWR data for each of the five core penetrations compared to the maximum in situ F-factor experienced during that event. Both the uncorrected TDWR F-factor and the altitude-corrected F-factor are shown. Also depicted are the alert thresholds of each sensor (0.105) and the ideal "line of agreement". The in situ and TDWR F-factors can be directly compared in this manner since both are tuned to a scale length that affects airplane performance. In the case of the in situ measurement this scale length sensitivity is achieved through gust-rejection filtering. With the exception of the rightmost point (event 143) the TDWR F-factor overestimates the in situ F-factor. When the altitude correction is applied though, the lower four events agree well. Considering that the two measurements are taken by different sensors on different platforms, and at slightly different times, the agreement is excellent. Of course much more data is needed to begin to assign statistical significance to this data. The reason for the relatively large TDWR underestimate of the F-factor for event 143 is related to shear estimation from TDWR products and will be discussed next.

# TDWR Based F and In Situ F

## Microburst Core Penetrations



## Shear Estimation from TDWR Data

Event 143 showed a substantial F-factor underestimate from the airborne algorithms when subjected to the altitude correction formula. The issue that arises is whether the altitude correction formula was incorrect in this case or whether another factor is involved. Examination of the moving map display video tape showed that the peak in situ F-factor was reached in the first third of the distance through the icon, as opposed to the center of the icon as would be expected. A plot of the along-track component of inertial winds as recorded on the aircraft during the penetration shows that the wind profile did not match the assumed profile between the peak winds. In particular, an intermediate peak in the wind was experienced about halfway through the event. This peak was nearly as large in magnitude as the peak outflow on the far side of the microburst.

The ground rules associated with this experiment prohibited changes to the ground system and led to shear estimation from information about the peak wind points. This requires an assumption about the wind profile between the peaks which, as is demonstrated here, will not always be true. In particular, pulsing microbursts may generate a microburst within a macroburst. The shear between the peak-to-peak winds may be low, but a smaller region of intense shear may exist within the outflow. This pulsing phenomena is observed both in field measurements and in TASS numerical simulation microbursts and may be very common (references 2 and 8).

The TDWR system is capable of directly locating regions of strong shear, as demonstrated by shear plots produced by MIT Lincoln Laboratory for post-flight data analysis, but the current alerting strategy does not require nor utilize this capability. Properly implemented, shear-based alerting could enhance the location of hazardous shears and improve the quantification of the hazard to aircraft.

# Shear Estimation from TDWR Data

- Ground rule to avoid changing the ground systems led to estimation of shear from:
  1. Data about outflow peaks.
  2. Assumed wind profile through microburst.
- In some cases assumed wind profile may not exist, i.e. microburst within macroburst, complex flow fields.
- TDWR can produce spatial shear measurement, not currently provided to users.

### Event 142 Along-Track Wind Profile and Shear Plot

Shown in the next graph and plot are the along-track component of inertial winds experienced by the aircraft during penetration of event 142 and the corresponding TDWR shear map plot.

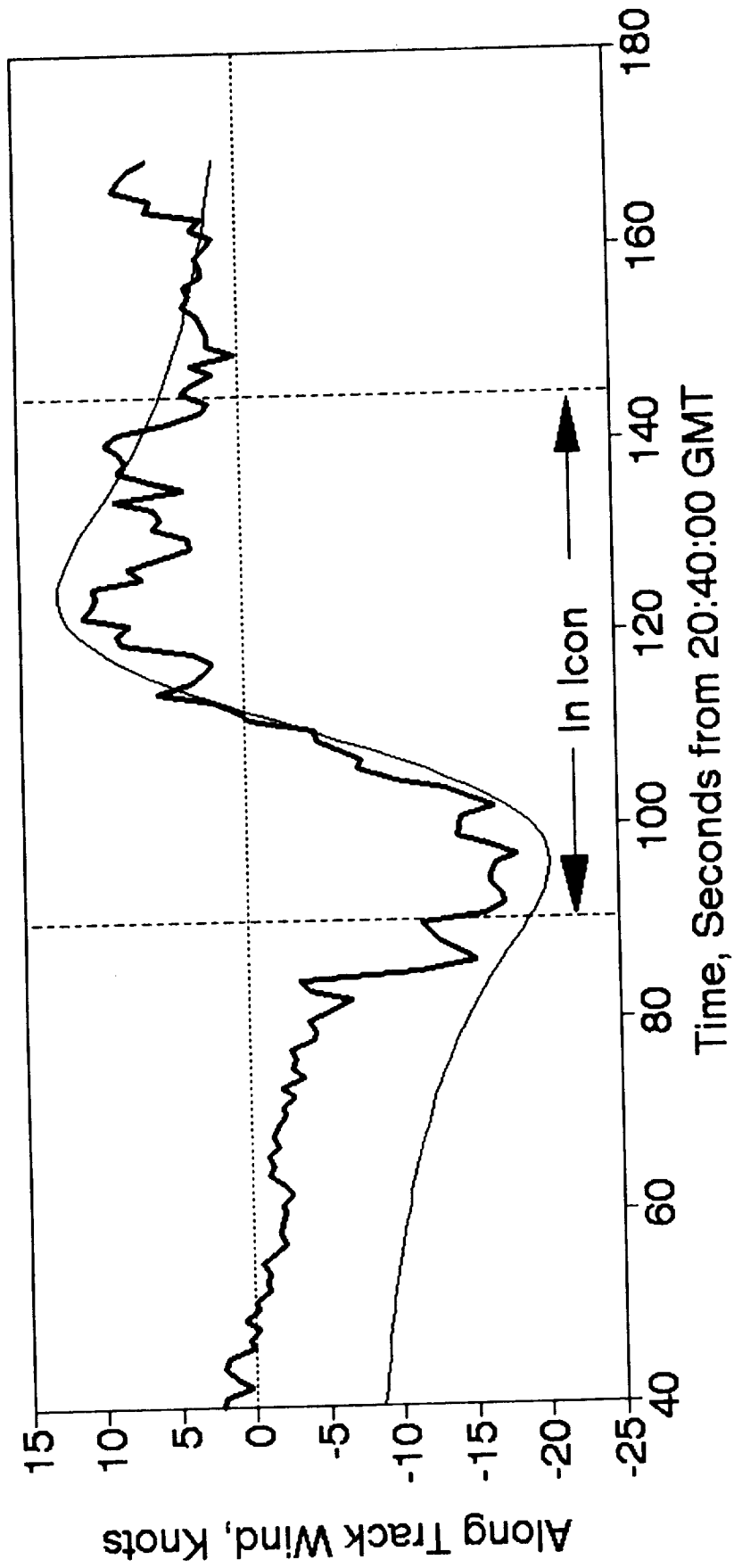
Superimposed on the inertial wind graph is the wind output of the Oseguera-Bowles analytical wind model. The inputs to the model are the  $\Delta U$  and  $\Delta R$  values provided by the TDWR for this shear. Although the in situ winds were somewhat less than predicted by the TDWR, the profile in the microburst core matches the shape of the predicted profile. Event 142 is the third data point from the left in the "TDWR Based F and In Situ F" plot shown earlier, and produced excellent agreement between predicted and actual F-factor when corrected for altitude.

The shear (meters/second per kilometer) of event 142 and airplane flight track are shown in the plot. This plot was generated from TDWR velocity data and provided to NASA by MIT Lincoln Laboratory. The shear plot agrees with aircraft in situ data in showing the region of strong shear in the center of the microburst icon.



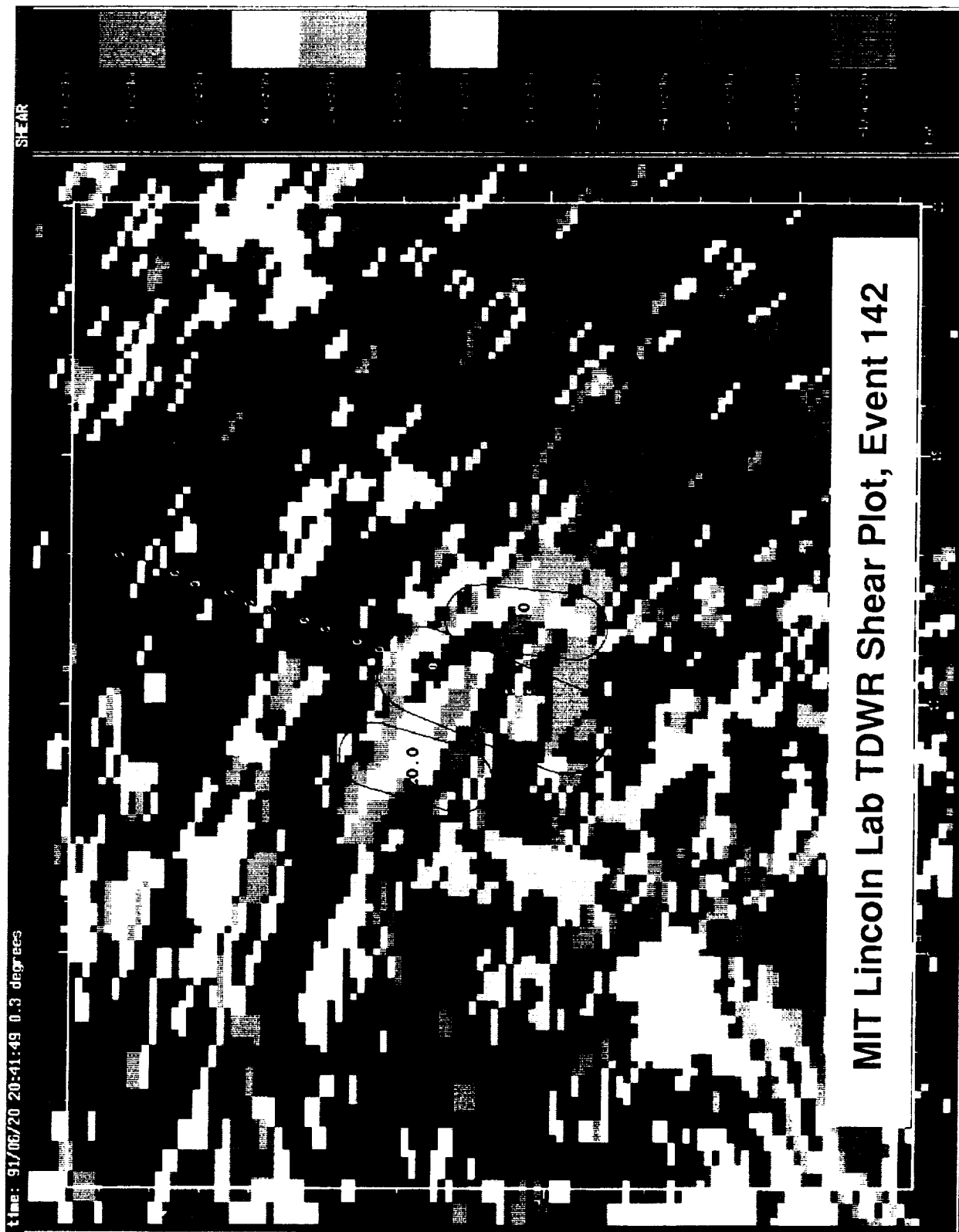
# Along-Track Wind Profile

Event 142 Microburst Encounter



— Aircraft Wind — Model Wind





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### Event 143 Along-Track Wind Profile and Shear Plot

The inertial winds experienced by the aircraft in event 143 are shown followed by the corresponding TDWR shear map plot. This is the same microburst as in event 142 but penetrated about four minutes later while traveling on a reciprocal track.

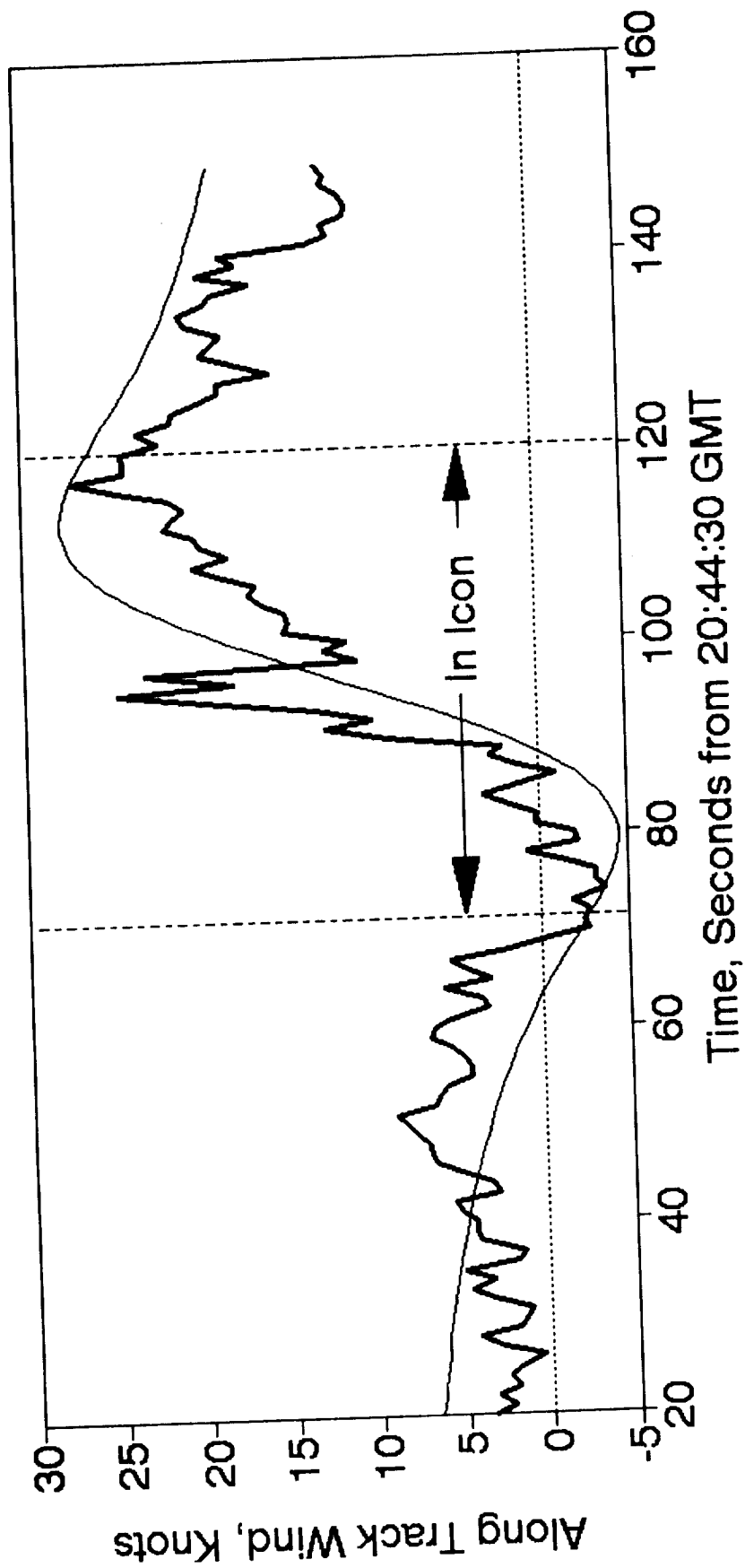
The event has expanded and a new outflow surge has developed. Event 143 is the rightmost data point in the "TDWR Based F and In Situ F" plot shown earlier. The inputs to the model winds in this case are the TDWR reported  $\Delta U$  (corrected by the altitude shaping function) and  $\Delta R$ . Since the TDWR-reported winds significantly overestimated the winds encountered, the altitude-corrected  $\Delta U$  is shown in order to more closely match the inertial wind peaks and compare the wind profiles. This plot shows a significantly greater than predicted shear in the first half of the icon penetration. This intermediate peak in the wind profile is responsible for the altitude corrected TDWR F-factor underestimate.

The shear in event 143 and airplane flight track are shown in the plot. The shear plot agrees with aircraft in situ data in showing the region of strong shear in the southern portion of the microburst icon. The flight data correlates very well with the shear plots and suggests that the TDWR is capable of accurately locating shear and measuring shear magnitude. Detailed data about microburst shear is available in the TDWR system but not made available in the current alerting strategy and data link system tested. Provision of this type of data to end users could better quantify the hazard and eliminate the need to estimate shear from wind measurements in airborne applications.



# Along-Track Wind Profile

Event 143 Microburst Encounter







Time: 91/06/20 20:45:51 0.3 degrees

SHAR





## Discrete Alerting Performance

To evaluate the overall alerting performance of the TDWR data link system as tested, all 19 microburst icon penetrations were considered. Out of these 19 events, 18 produced airborne TDWR alerts while only 2 produced in situ alerts. By far the predominant factor producing this nuisance alert rate is the spatial effect of not penetrating the microburst core in most of the events. The F-factor estimation is not valid for any arbitrary path in the vicinity of the microburst. Although a separate F-factor was computed for each icon, the division of one microburst into multiple icons was such that any given icon did not necessarily contain the core of a microburst downflow. Penetration of these icons resulted in a significantly lower in situ F-factor than predicted. The second factor affecting alerting performance was the altitude effect described earlier. When adjusted for altitude, fewer icons exceed the alert threshold.

The final factor affecting alerting performance was temporal. A microburst can grow or decay in the one minute interval between updates. In the penetration of event 142 the airborne TDWR alert was received after the airplane entered the microburst event and a new data link update was received. Since this event did not exceed the in situ alert threshold the TDWR alert was counted as a nuisance alert rather than a late or missed alert. Although nuisance alerts caused by decaying events are probably inevitable with any remote or forward look sensor, the issue arises as to the possibility that an alert will be missed on a significant event. This type of missed alert requires that the F-factor increase from below threshold to a truly hazardous level between TDWR updates, and that the airplane enter the event between those updates. Insufficient data was gathered during the flight tests to estimate the frequency of this occurrence, although the potential for this situation was demonstrated in an aborted microburst approach when the TDWR F-factor estimate increased from 0.18 to 0.26 between updates.



# **Discrete Alerting Performance**

<b>Microburst shape penetrations:</b>	<b>19</b>
<b>Airborne TDWR alerts:</b>	<b>18</b>
<b>In Situ alerts:</b>	<b>2</b>

**Primary factors affecting alerting performance:**

- Spatial, many icon penetrations missed microburst core.**
- Altitude difference, measurement and encounter.**
- Temporal, intensity changes between updates.**

## Plans for 1992 Research Flights

Numerous changes are being made to the TDWR processing and the flight operation to enhance system performance and data opportunities during the planned 1992 wind shear flight tests. The altitude correction technique developed during this data analysis will be implemented onboard the aircraft for real-time application. Appropriate limits will be set in the altitude correction so that the algorithm functions realistically while on the ground or when the airplane is loitering at a higher altitude than would be used for penetration. On the ground the algorithm will calculate an F-factor applicable to an initial climb speed and altitude. At high altitude the F-factor will be applicable to the altitude range used for penetrations. The alert criteria will also be modified to prevent alerts during ground taxi due to microbursts near the airport as well as when airborne above 1500 feet. In 1991 numerous alerts were received while the aircraft was on the ground and microbursts were ahead (none of these alerts are included in the analysis.) In 1992 these alerts will not be given unless the airspeed is at least 60 knots, indicating that takeoff roll is in progress. Of course the microburst icons will always be displayed.

To increase the number of microburst core penetrations, the aircraft coordinator at the TDWR site will be provided with a real-time range/azimuth display of shear. This display, along with the waypoint feature of the data link, will be used to communicate the most promising locations to the airborne crew. At the suggestion of Dr. Steve Campbell of MIT Lincoln Laboratory, a "waypoint-with-shear" data link product will be tested. The concept is to make a direct one-kilometer shear estimate at the TDWR site of a region about the designated waypoint, and transmit this shear value to the aircraft for use in F-factor estimation. This will eliminate the process of estimating shear from the peaks of the wind outflow for events marked with such a waypoint. The normal F-factor processing of the microburst icons will continue to be performed for all events.

Finally, the demonstration of an "automated pilot report" capability on the data link is planned. In numerous events (ref. 2) pilots have encountered wind shear and not provided timely pilot reports to ATC. The controllers and subsequent aircraft may not have the benefit of knowing why the earlier aircraft missed the approach. The automated pilot report will downlink the status of wind shear alerts from onboard systems. In the NASA flight tests this alert information will terminate at the TDWR site and will not actually be provided to ATC.

## **Plans for 1992 Research Flights**

- Provide real-time altitude correction.
- Modify alert criteria to prevent alerts at high altitude or during taxi.
- Provide TDWR aircraft coordinator with real-time shear map to enhance ability to hit core of microbursts.
- Evaluate F-factor estimate from direct TDWR measurement of 1 kilometer shear in vicinity of waypoint (MIT Lincoln Lab suggestion).
- Downlink "automatic pilot report" from aircraft to NASA ground station.

## Summary

This experiment demonstrated the feasibility of transmitting ground-based wind shear information to an aircraft via data link, processing that information on the aircraft to estimate the wind shear hazard index (F-factor), then providing the information on a moving map display for operational use. In the limited number of microburst core penetrations experienced, the estimated F-factor compared very favorably to the actual in situ F-factor. More cases are needed to show statistical significance.

As the current system was implemented, the executive level alerting performance was inadequate due to an excessive number of nuisance alerts. These nuisance alerts were due to inadequate data being available to the alerting process to precisely locate the region of strong shear, and the aircraft trajectory not intersecting those regions. The information required to minimize this limitation is resident within the TDWR system but not planned as an output product of production TDWR systems. More complete use of the ground system capabilities may greatly improve the utility of the TDWR microburst information to the end users.

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## **Summary**

- Demonstrated feasibility of data link and airborne use of TDWR microburst information.
- F-factor estimation from TDWR data reasonable in very limited number of microburst core penetrations.
- Alerting performance inadequate "as is" for executive level crew warning. Improved shear location required.
- Results suggest that full capabilities of ground system should be used to provide shear data to users, airborne F-factor estimation may be improved given data link of shear values.
- Altitude correction required for radar data at research speeds.

## **Air/Ground Wind Shear Information Integration - Flight Test Results**

### **Questions and Answers**

**Q: Norm Crabill (Aero Space Consultants)** - The shape of these icons sort of bothers me a little bit. I was wondering if the racetrack pattern has its long axis along the radius vector from the Doppler. Is that correct?

**A: Dave Hinton (NASA Langley)** - In these cases it did.

**Q: Norm Crabill (Aero Space Consultants)** - So that is a limitation of the single site ground determination of the velocity field. If you were making an approach to a runway that was at right angles to that, you are not going to get a lot of information. What have you concluded about TDWR siting relative to the runway? How do you use this information to help you site the TDWR now that they are being deployed?

**A: Dave Hinton (NASA Langley)** - We did not try in our analysis to do that.. Our ground rules were not to change the TDWR system, so we did not look into siting issues per say. There are some very good historical reasons for why those shapes are the way they are, and I'll let Steve Cambell cover that.

**A: Steve Cambell (MIT Lincoln Laboratory)** - That is a good point Norm. Basically, what we originally started out with was a big region that we identified as a microburst. Then we decided to do a better job of isolating where the strong velocity change was by dividing this shape up in the azimuthal direction. I will talk a little bit about this on Thursday, and about some of the ideas we have for doing a better job of localizing the region of peak shear. But you make a very good point, and that is one of the things we are currently looking at; how we can improve that shape representation.

**Q: Norm Crabill (Aero Space Consultants)** - What about the question of TDWR siting, and some practical situations?

**A: Steve Cambell (MIT Lincoln Laboratory)** - That is another issue too. We have done extensive testing where we use dual Doppler Radars to determine the shear for approach or departure paths and we have been able to show that we can do a pretty good job of estimating the shear or the change in velocity along the flight path with a single TDWR. The deployed TDWR's will be deployed in conjunction with the enhanced LLWAS system, which is a surface base anemometer system. If you have a situation with a highly asymmetric microburst then the LLWAS system should be able to detect it. Now we have also studied this issue of how likely is it that the outflow would be highly asymmetric. Generally, in the South East they are not very asymmetric. You do see asymmetric ones in places like Denver though; so in that case we think that the surface sensor would be a fail safe for making sure we detect the strong shear of any region perpendicular to the radar beam.

**Norm Crabill (Aero Space Consultants)** - Well of course the LLWAS alarm at Dallas was after the fact.

**Steve Cambell (MIT Lincoln Laboratory)** - I should point out that we are integrating with the enhanced LLWAS system. The current six station LLWAS is not really adequate for microburst detection. The enhanced LLWAS system have something like a 13 to 16 stations. It's a much more extensive LLWAS network which covers most of the approach and departure paths. It also has a different algorithm than that used in the current Phase I LLWAS. We have been able to show that when you integrate TDWR and the enhance LLWAS there is a very high probability of detecting a hazardous wind shear along any arbitrary path. So we are very confident. Both systems work very well and when you combine the two you have an extremely reliable system. We have been able to verify that against our dual Doppler measurements, and other measurements.

**Norm Crabill (Aero Space Consultants)** - Dual Doppler is handy, but you won't have it at those forty-six sites.

**Steve Cambell (MIT Lincoln Laboratory)** - The dual Doppler is for the purpose of generating the truth so we know what actually happened. We are validating our single Doppler with the surface sensors against dual Doppler.

**Q: Sam Shirck (Continental Airlines)** - With respect to the TDWR results, is it possible that in the future airborne radar systems may data link their view of the wind shear situations to the ground based TDWR, since the airborne systems have a better viewing angle and a much enhanced update rate?

**A: Dave Hinton (NASA Langley)** - I think it certainly would be possible to down link the data to the ground base system. The primary obstacle standing in the way is going to be the lack of a system driver for doing that. Within the context of the program we are doing, we have a charter not to change the ground system. Now, if there is a system requirement to do that, it could possibly be done. There are a couple of technical issues involved; one is the data rate that would be required to get that amount of information down, and secondly a lot of dual and triple Doppler analysis' have been done of numerous events and that can take, I would expect, a significant amount of post processing. To do the triple Doppler analysis in real time would probably be a very large computational effort. So it is a question of a system driver plus the effort involved to do it.

**Jim Evans (MIT)** - Where the ground systems are going in the relatively near future is toward what is called integrated terminal weather systems, which in fact tries to integrate information from all the available ground and airborne systems. We are already talking about ingesting winds and temperature data out of planes. I don't think it is a big issue to transmit that information down over a Mode S data link. I think what you would do is that you would formulate it as a message, it would then come up as an additional piece of alert information that could be passed along in much the same style and thereby provided automatically to succeeding planes. I do not think you would have to get into dual or triple Doppler analysis.

**Dave Hinton (NASA Langley)** - Obviously, you could operate such a system at various levels, triple Doppler being the most complex. Another way would be to simply look at alert regions and use those in some manner. Which Jim, if I understand, is what you are referring to.

**Jim Evans (MIT)** - I think I would try that for starters, because I think the others would be fairly complicated. One of the issues that you would get into immediately on dual or triple Doppler, with an airborne weather radar at X-band, would be the whole question about how well you had unfolded your velocities. You don't have to unfold absolutely to get shear regions, but you could be off by a whole fold without any trouble at all.

**Q: Norm Crabill (Aero Space Consultants)** - I would like to revisit the question of TDWR siting. I don't know to whom I should address the question, but if you have an airport like O'Hare with intersecting runways, where do you put the terminal Doppler radar?

**A: Jim Evans (MIT)** - It is fairly simple. What we have used as the criteria in siting the TDWR is to look at the runway usage during circumstances when there is weather, and try to line up the TDWR to look along those runways. We then do an adjustment in cases where there are split runway regions. O'Hare is certainly the ugliest case one can point to. In most of the others, it is a fairly reasonable site. We have tried to consider looking up the runways the maximum amount of the time consistent with when the weather was going to be present. It is a lively task of course, in a place like Leguardia, just trying to find a place to put the radar. I think we have been very successful.

**Q: Norm Crabill (Aero Space Consultants)** - If you have intersecting runways and low weather, and conditions conducive to microbursts, is there any intent to restrict the operations to the runway that is favored by the terminal Doppler weather radar?

**A: Jim Evans (MIT)** - Again, we don't see the need to do that. What we have been trying to do is assess the performance by taking dual Doppler measurements of the winds along the runway. There is certainly ample reason to believe that dual Doppler does a very good job of estimating the winds. What we do is we look at the winds along the runways no matter what there orientation is, whether the TDWR has a good look angle or a bad look angle, and assess the accuracy of the warnings. For example, if the actual wind along the center line of the path had more than a 30 knot wind change over a suitably small distance we would check to see if we are issuing an alert or not. It is a very high probability that we do, no matter what the orientation of the runway is. That is what we have seen for Denver, Kansas City, and Orlando. In that process we use runways that we have lousy look angles to. The reason that we know what the winds are is because we have dual and in some cases triple Doppler data to tell us what the winds are. That is the way we are trying to assess it. Are we giving it a timely warning for that runway? Sure, it is a little better on the ones that you have a nicer look angle, but it doesn't mean that you are not detecting, very reliably, all the ones at any angle you want to imagine a runway to be.

**Norm Crabill (Aero Space Consultants)** - Someone keeps bringing up in this discussion, dual Doppler. My understanding is that there is only one TDWR per airport.

**Jim Evans (MIT)** - Let me again make it clear what is being done. From a research basis, we go to airports with two and three radars and we evaluate quantitatively our performance. We score a single radar's ability to give accurate warnings on all the runways. You say, how did you know what was there. The reason we know what was there is that we had dual or triple Doppler. Now when we go out in the actual operational system there is only one radar at the airport. But, we

believe we know what its performance is going to be. This summer will be our seventh year of testing with dual Doppler data. We think by doing this testing over a wide variety of airports and geographic regions and having synthetic runways as well as real runways, we have a very good handle on the performance of the system. That is the rule. It isn't that a operational system has dual or triple Doppler, it is that we have done careful experiments with dual and triple Doppler and supporting mesonet systems. Is there a microburst the radar can't measure. We have gone out and tried to address that number in this phase. That is what we are quoting from and we hope the past is a prediction of the future. Of course, the world may change. This is one of the most carefully tested systems that I know of.

**Q: Norm Crabill (Aero Space Consultants)** - Yes, I agree there has been a lot of testing. What has been the result for Chicago where will the radar be located?

**A: Jim Evans (MIT)** - We have not done dual Doppler testing yet at O'Hare. The radar will be almost due south of O'Hare. There is an ARSR site down there it is roughly to the east of Midway. It is a location that will give a good look at both Midway and O'Hare.

